Properties of High-Intensity EUV & Soft-X Radiation Plasma Sources

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Sources for EUV Lithography

Diffraction restricts the resolution

$$r \geq k_1 \frac{\lambda}{NA}$$

NOW
EUV for HVM
beyond 16 nm

λ ⇨ 13.5nm ⇨ 6.Xnm
($h\nu$=92eV ⇨ 185eV)

$\delta\lambda/\lambda$ ⇨ 2%

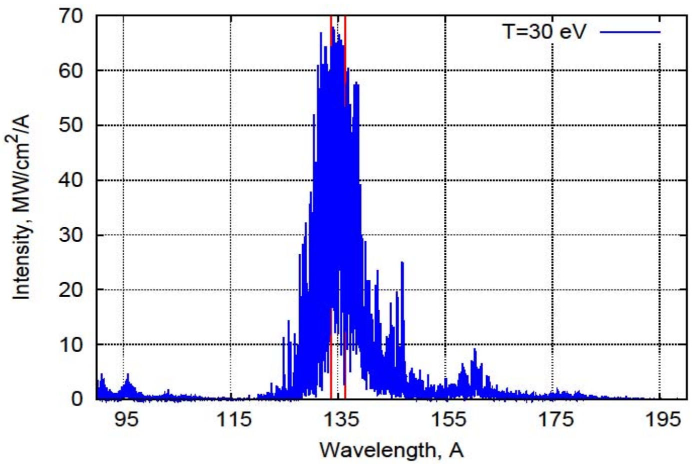
Nano-Age World

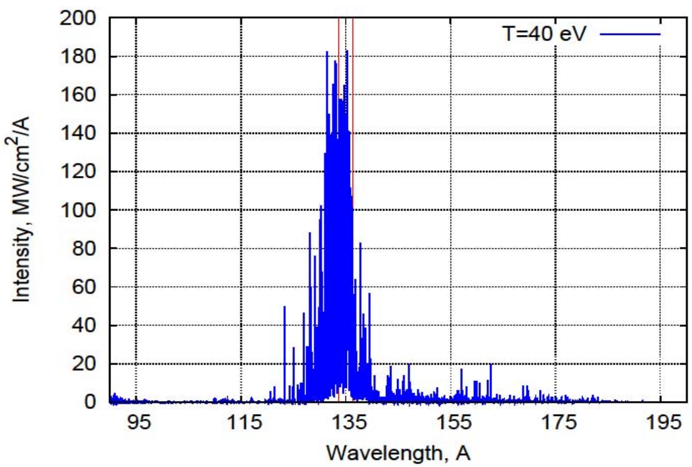
The optics is made of multi-layer mirrors with reflection efficiency ~70%

- For HVM: >> 200 W of in-band power at IF within < 3mm^{2}sr etendue
- For mask inspections ABI→AIMS→APMI : 30 → >100 W/mm^2·sr

Sn, Xe… High Energy Density plasma
(T_e=20-40eV) radiates in EUV range
LPP & DPP

EUV Brightness Limit for EUV Source



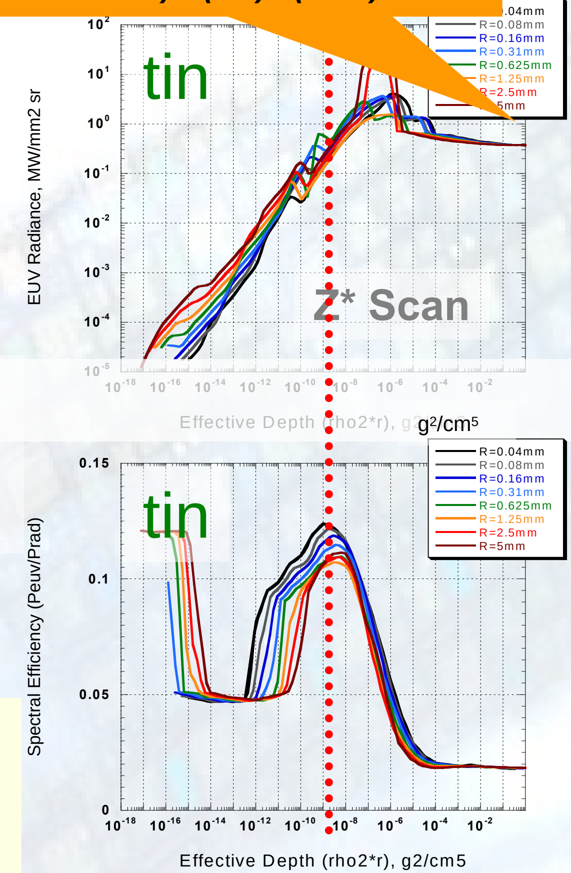


Detailed spectra from tin plasma with radius R=100 μm and $n_e=10^{19}$ cm^{-3}

Spherical model of tin plasma EUV source

RMHD scan for tin plasma optimized by radius, temperature and density [AL10]

$L \approx 1.1(W/mm^2\ sr)\cdot\tau(ns)\cdot f(kHz)$



The radiation self-absorption limits the in-band EUV radiance from the plasma, and the etendue constraint limits the usable power at IF of a conventional single unit EUV source

EUV Brightness Limit at Higher Temperature

LTE

- **The intensity upper Planckian limit of a single spherical optically thick plasma source in $\Delta\lambda/\lambda$=2% band around λ=13.5nm**

$$I = \frac{2hc^2}{\lambda^4}\frac{\Delta\lambda/\lambda}{e^{\frac{hc}{\lambda T}}-1} \approx \frac{72}{e^{\frac{92}{T(eV)}}-1}(MW/mm^2 sr)$$

- **Source with pulse duration τ and repetition rate *f* yields the time-average radiance** $L = I\cdot(\tau f)$

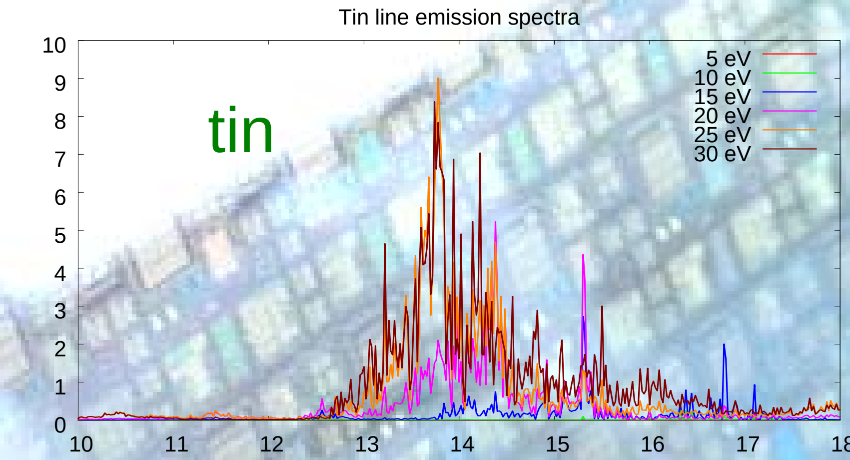
- **The spectral efficiency has the maximum at $T \approx 22eV$**

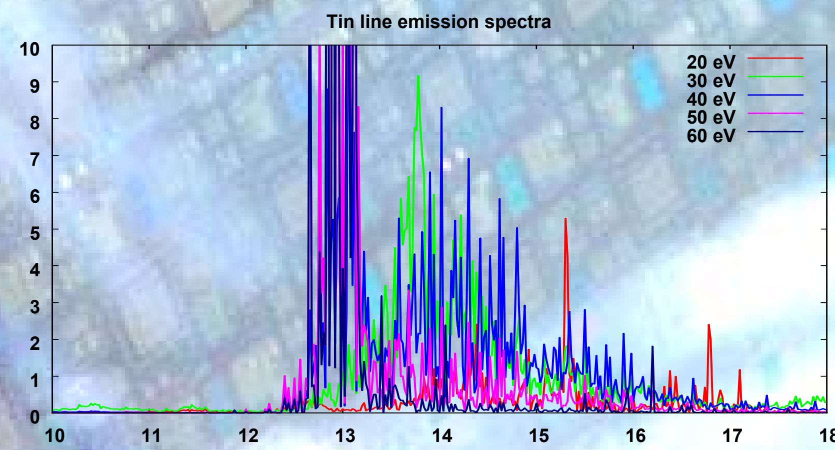
  $L \approx 1.1(W/mm^2 sr)\cdot\tau(ns)\cdot f(kHz)$

- **For instance, at τ =20ns**

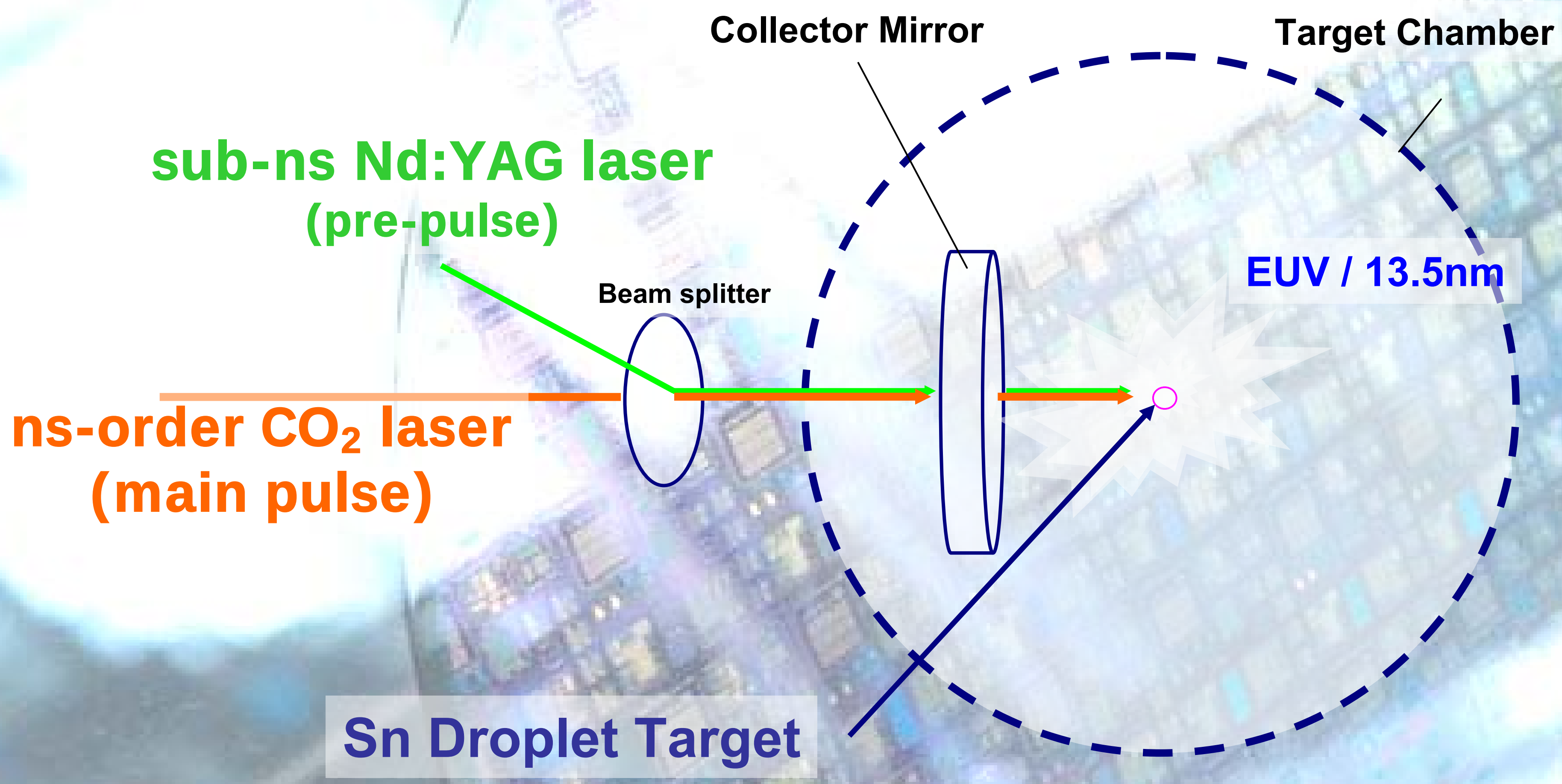
  $L = 22\ (W/mm^2\ sr)/kHz.$

Non-LTE



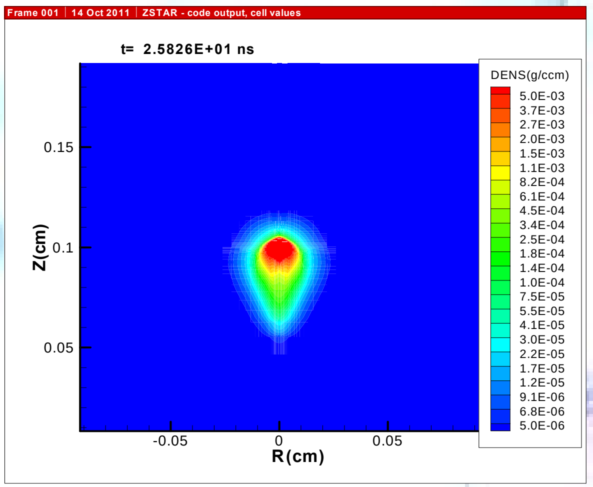


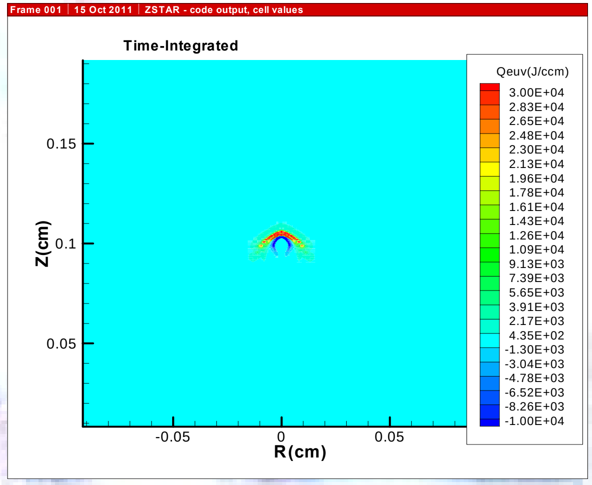
Combined Nd:YAG - CO_2 Laser System

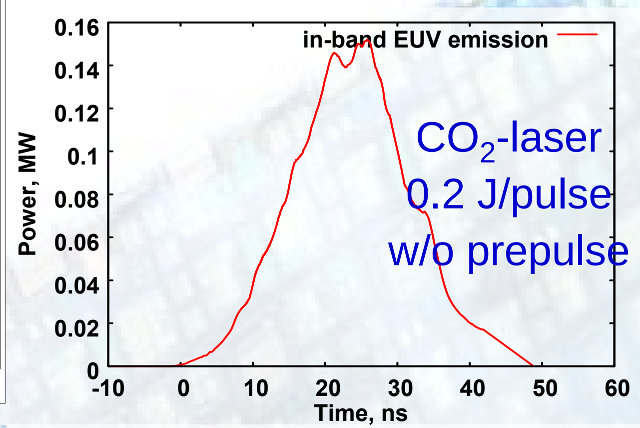


LPP EUV Source

under CO_2- laser or combined pulse

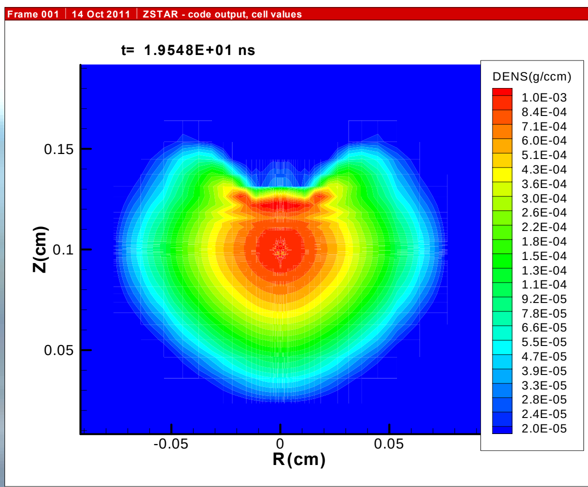


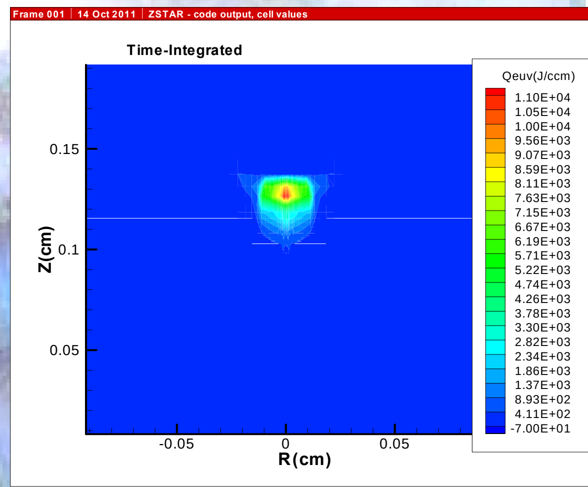


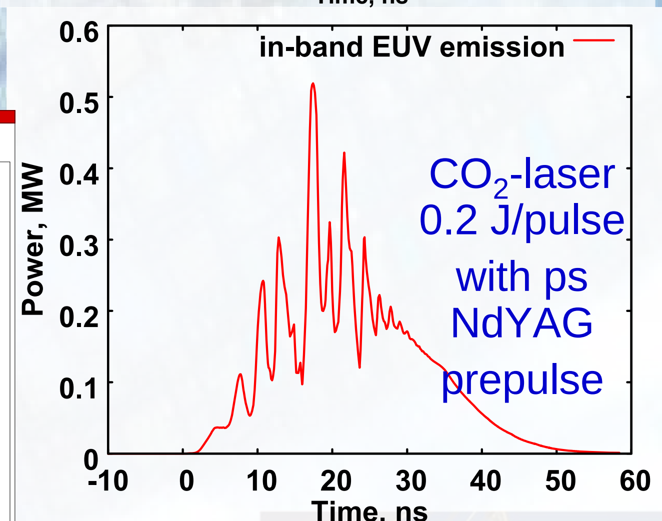


Tin plasma density at EUV maximum

Time-integrated EUV source image







The maximum EUV brightness is up to15 W/mm² sr kHz

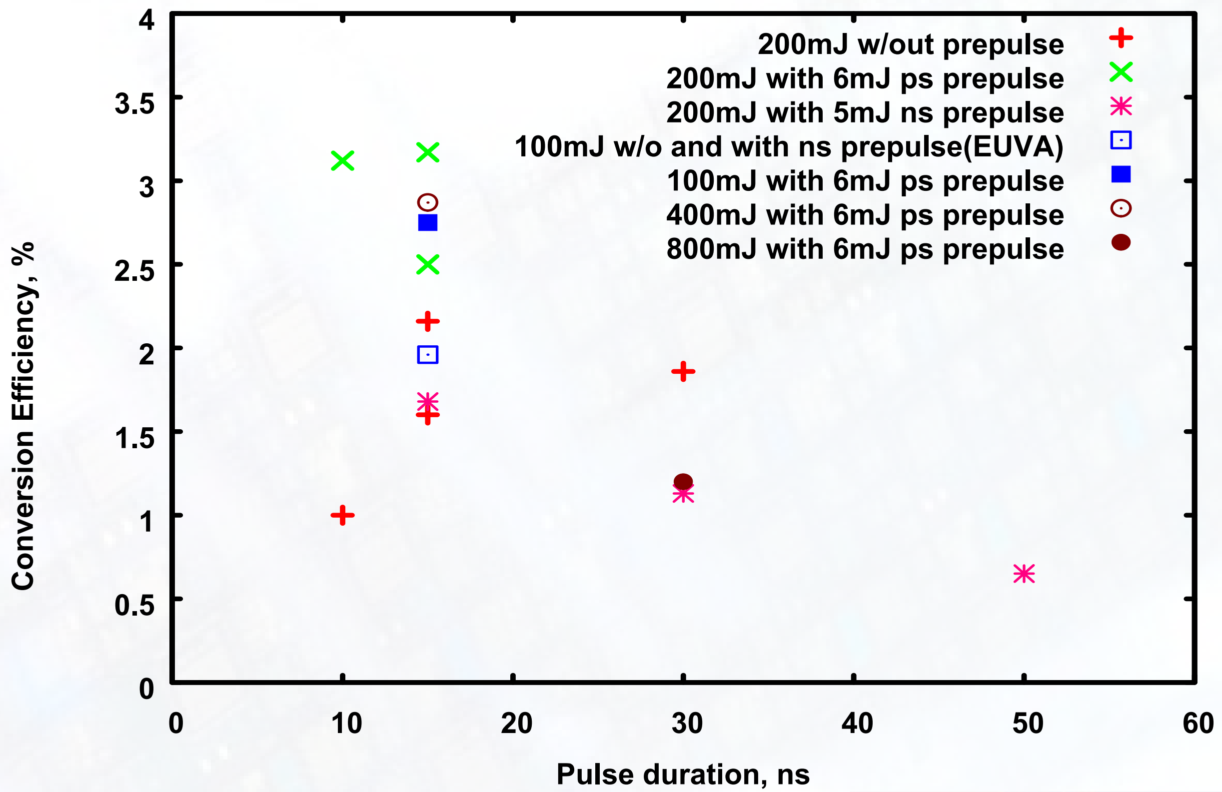
Conversion Efficiency of CO_2-laser on pulse duration, with & w/out pre-pulses

Main pulse: CO_2-laser 0.1-0.8 J/pulse, 10,15,30,50ns fwhm, 200μm focal spot
Pre-pulse laser (if applied): Nd:YAG 5 mJ 1-10ns pulse, 40μm spot size
or Nd:YAG 6 mJ 10-100 ps pulse, 40μm spot size

Target:
Liquid tin droplet of 40μm diameter
or
20μm for 100mJ (EUVA)

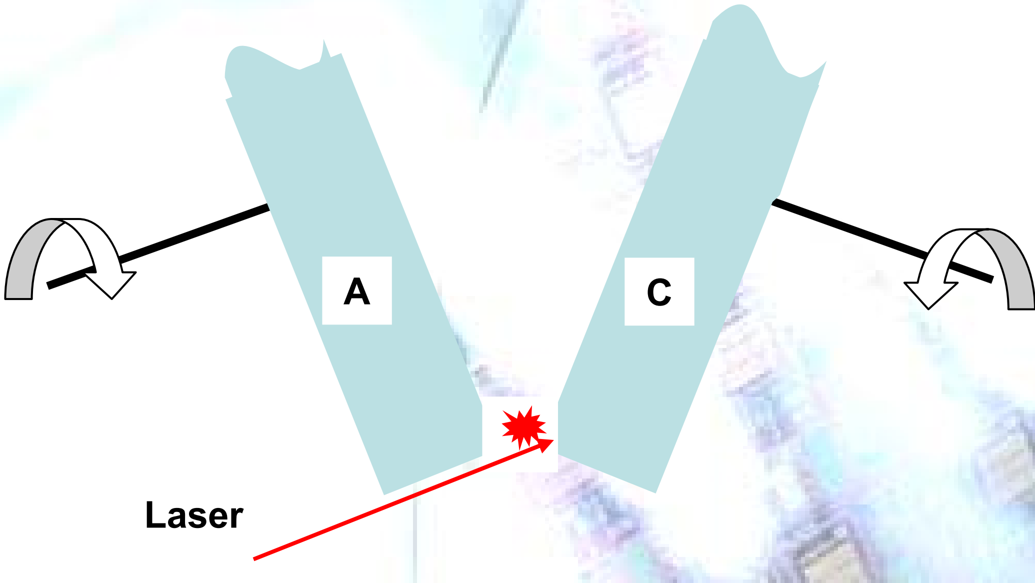
Conditions:
different focal positions;
different time delay between pre- & main-pulse

CE depends strongly on laser intensity and target irradiation conditions



CE maximum of 3% can be reached at laser energy (200mJ) in a combined ps-ns pulse

Laser Assisted Vacuum Arc (LAVA-lamp)



High-current discharge between two rotating electrodes covered with a thin liquid Tin or Galinstan film is triggered by local laser ablation of electrode material.

Discharge

capacitance	0.4 μF
inductance	19 nH
voltages	3 – 6 kV
energies	1.8 – 7.2 J
current	20 kA at 4.5 kV

Trigger laser:

wavelength	1064 nm
beam diameter	3 mm
focal lens	30 cm
energy	5 – 50 mJ

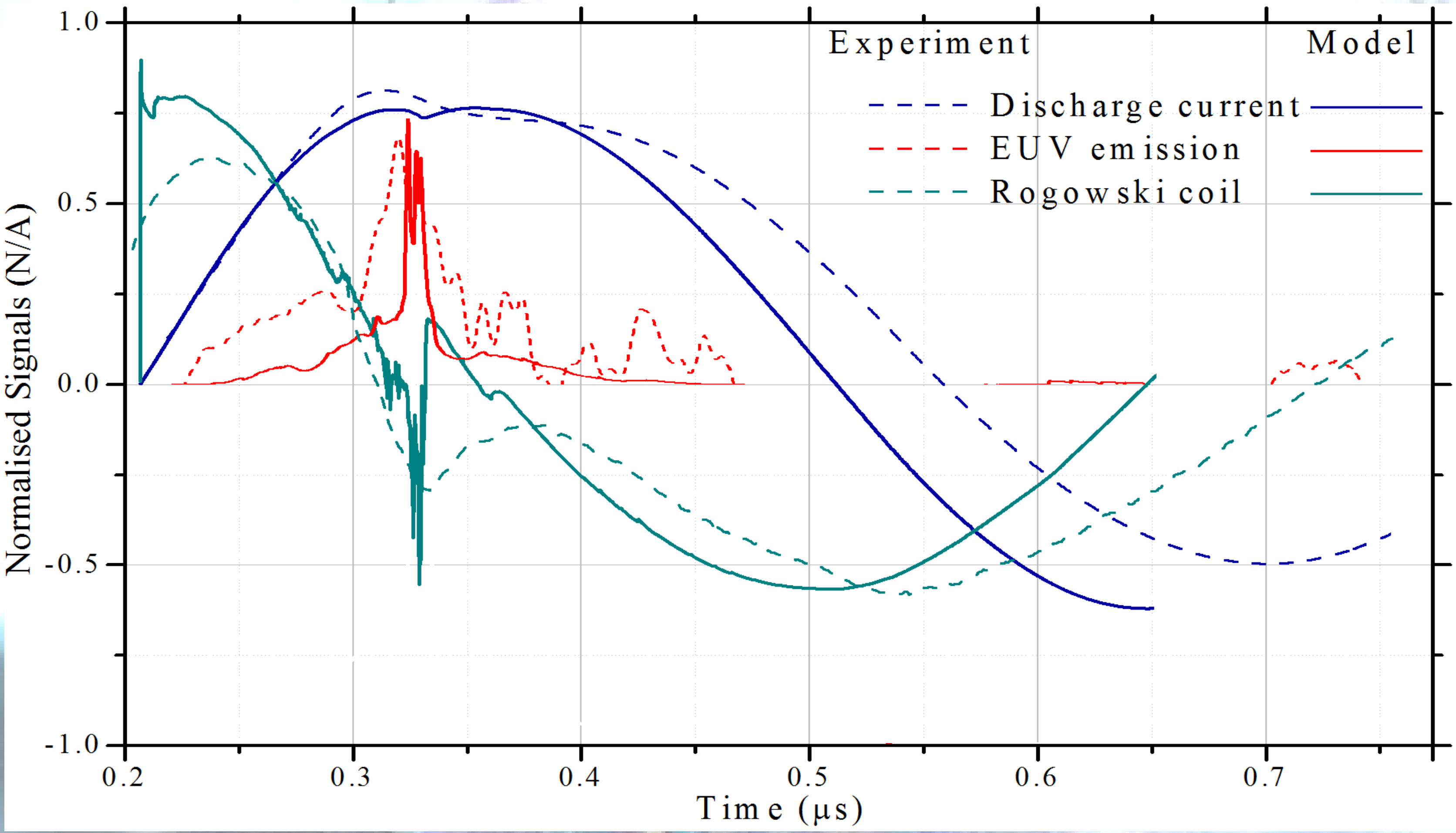
(varied by means of rotatable half-wave plate and polarizing beam splitter)

Details are presented in the posters :

S26 V.S. Zakharov, Larissa Jushkin, S.V. Zakharov et al

S30 Isaac Tobin, Larissa Juschkin, Vasily S. Zakharov et al

Comparison of measured and Z* modelling
discharge current and in-band EUV emission

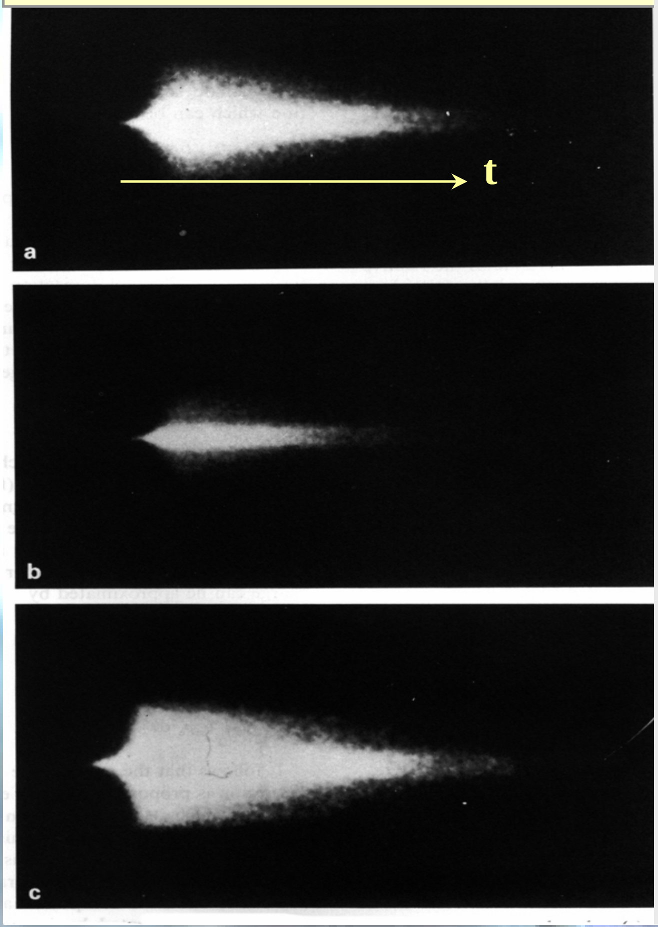


tin

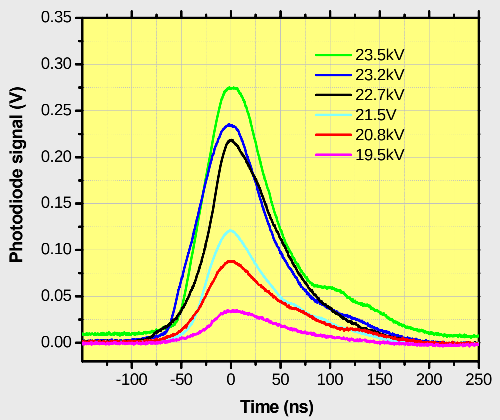
Capillary Discharge EUV Source

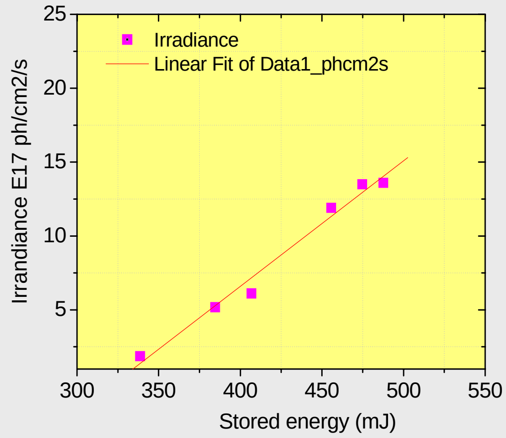
EXPERIMENT: discharge glow & EUV emission

optical streak photograph

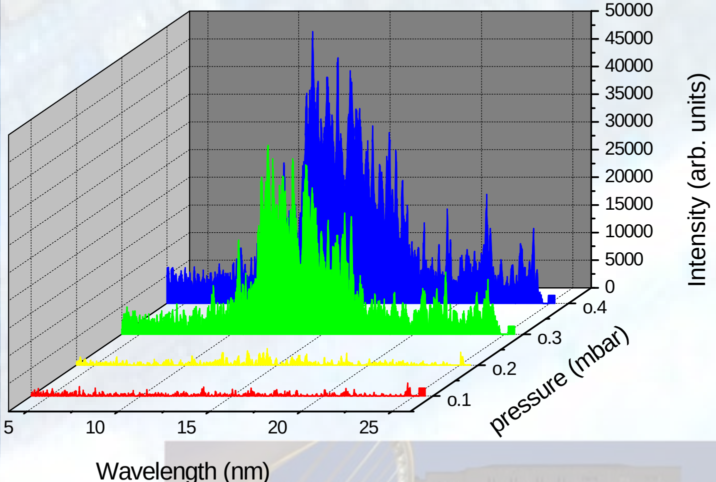


EUV emission





EUV spectrum



High Brightness EUV Plasma Source
pulsed capillary discharge

Power source

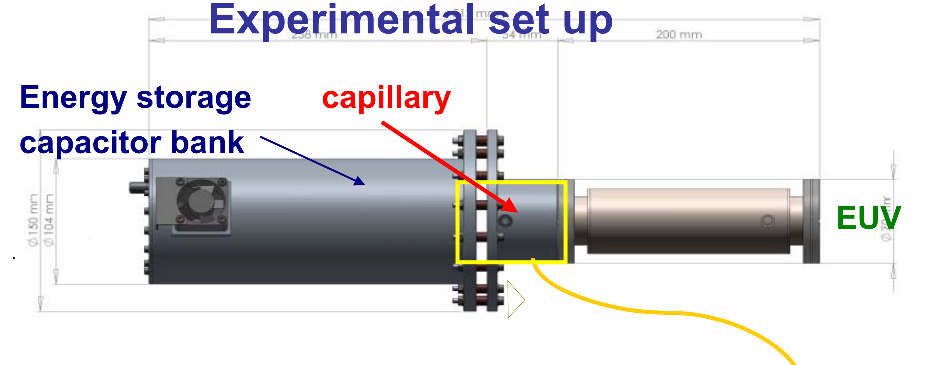
Charge energy	0.2 – 0.5 J
Current	5 - 10 kA
Pulse	~10-20 ns
Capillary dimension:	∅ 1.6 mm L = 12-18 mm

Various electrode geometries

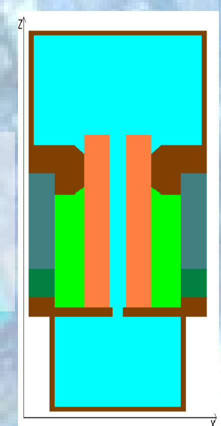
Gas:

0.02-2 Torr gradient He;
Xe, N_2, Ar, Kr,, … admixtures
(for narrow-band radiation source)

Experimental set up



Example of simulated geometry



Capillary discharge dynamics & emission features:

E-beam, plasma channelling (ε>>1)

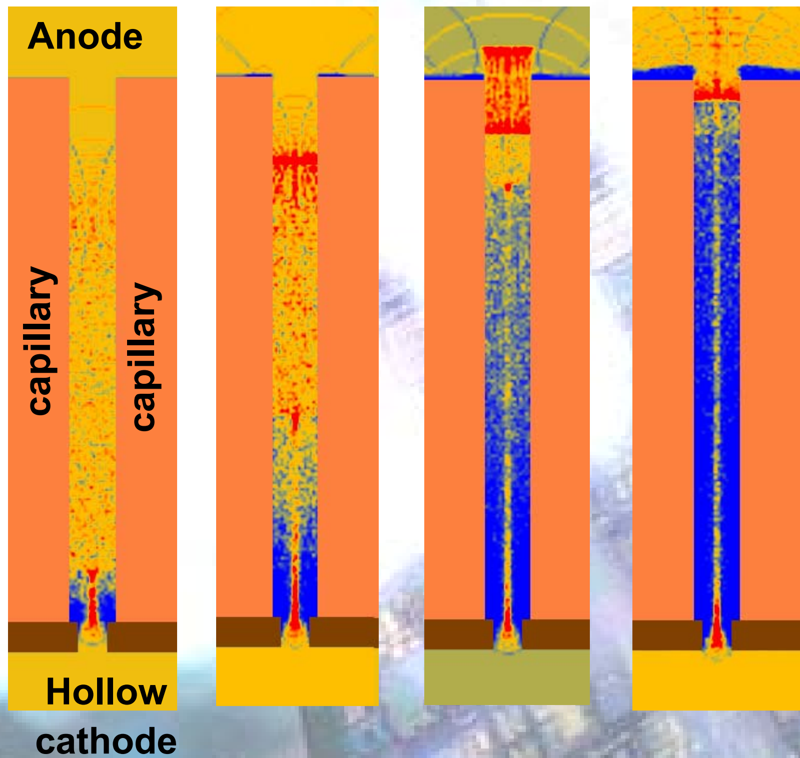
Volumetric MHD compression (skin depth >>plasma diameter)

Highly ionized ions (fast electrons)

Hollow-cathode Capillary Discharge

modelling: triggering by fast electrons

together with Markov M.B. et al, KIAM RAS



Electron beam in the HC capillary discharge

⇒ run-away electrons

⇒ electric field drops deeper into HC

⇒ e-beam concentration (ε >>1)

⇒ e-beam-gas ionization

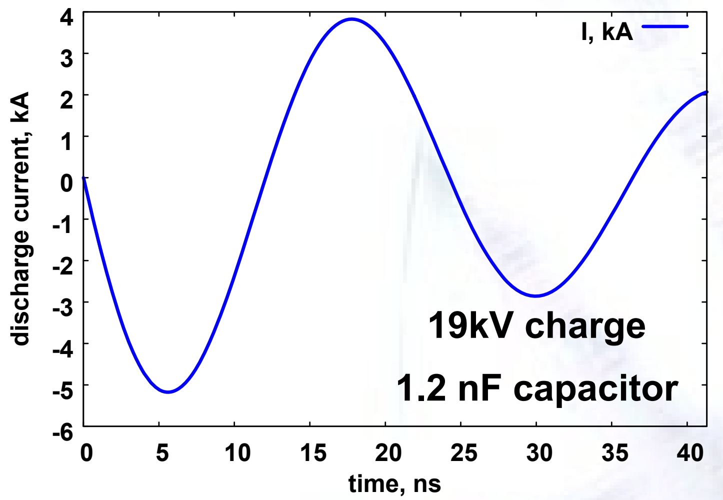
⇒ ionization wave

In the first few nanoseconds, run-away electrons from the hollow cathode generate a tight ionized channel (< 200μm diameter) in the gas

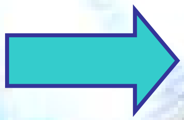
Capillary Discharge EUV Source

Z*-code modelling: resistive regime

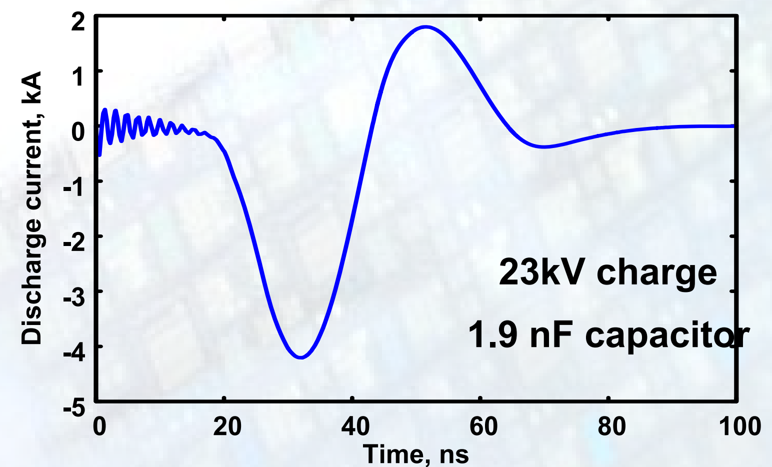
Inductive regime



Nitrogen as buffer gas



Resistive regime

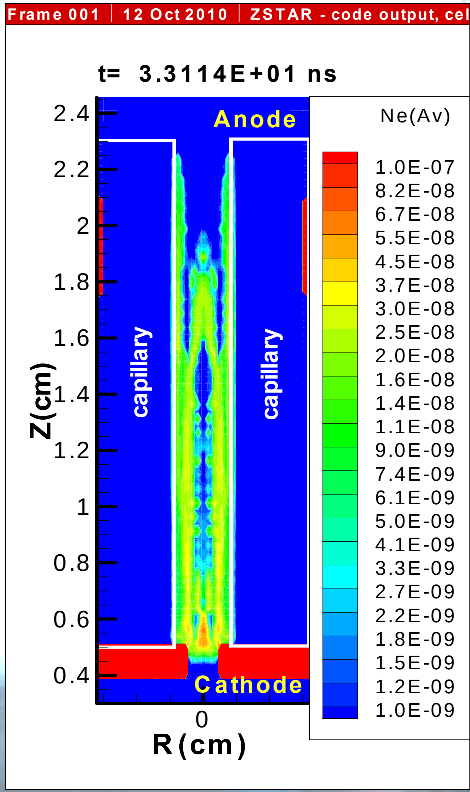


In the resistive regime of capillary discharge, the high joule dissipation in the tight conductive channel produced by hollow cathode electron beam creates an efficient mechanism of plasma heating and EUV or soft X-ray emission.

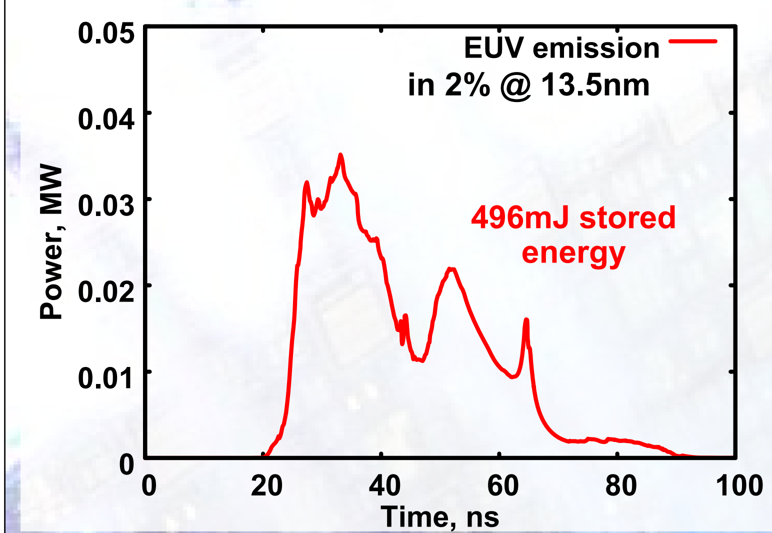
Also, fast electrons increase the ionization degree of heavy ion (Xe,…) plasma increasing eo ipso EUV yield.

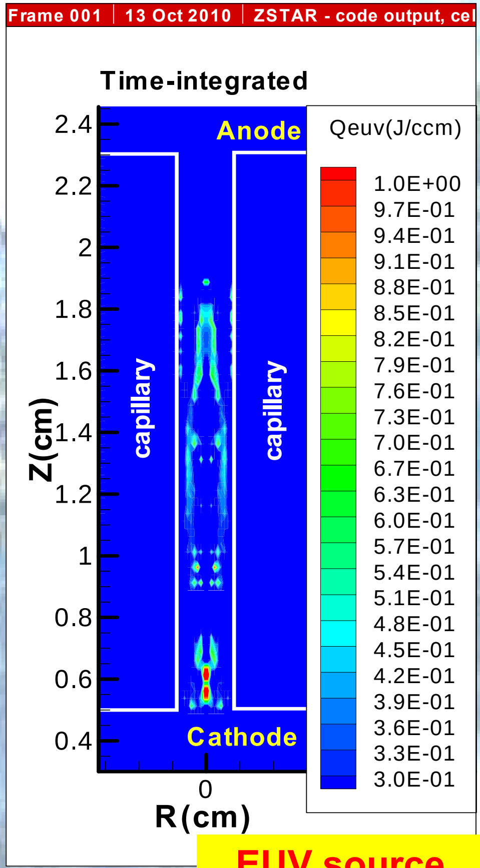
Capillary Discharge EUV Source
dynamics & EUV emission

3D volumetric compression



N_e=2-3 $\cdot 10^{17}$cm^{-3},
T_e=25-40eV.





EUV source cross-section

The traced along the axis, EUV intensity at 13.5nm wavelength

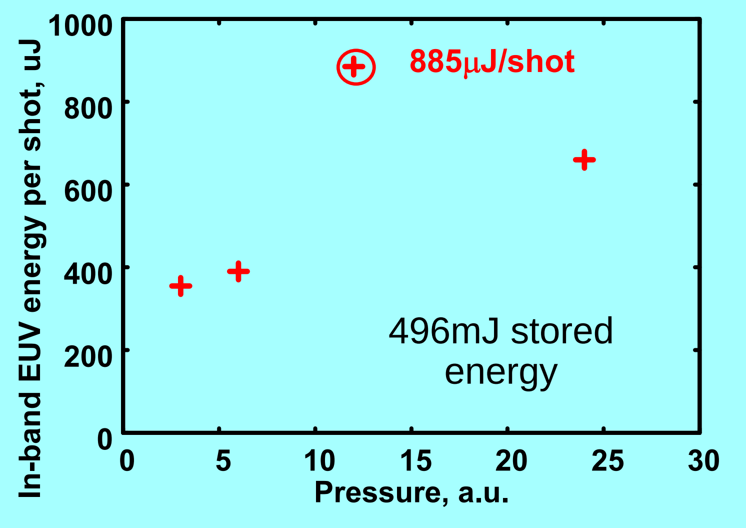
15.3 W/eV mm^2 sr per kHz

Calculated in-band EUV emission

0.885 W/kHz

Capillary Discharge EUV Source

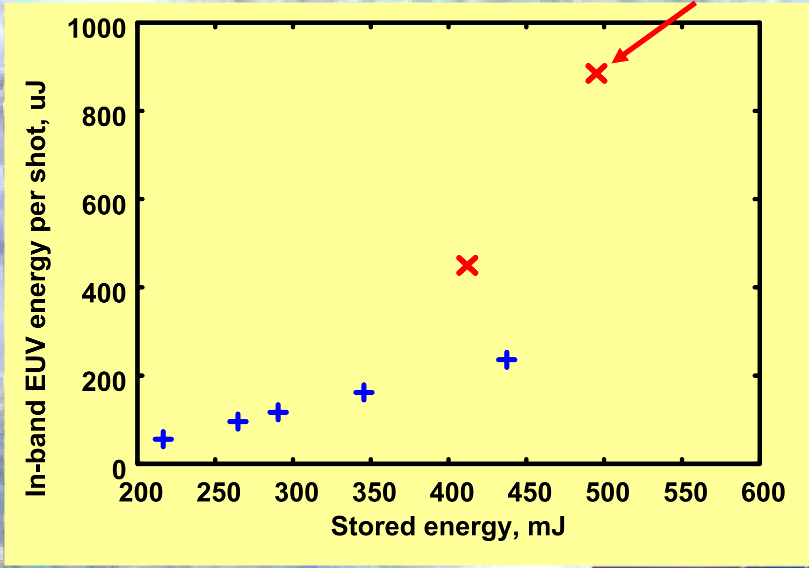
Z*-code modelling: source optimization



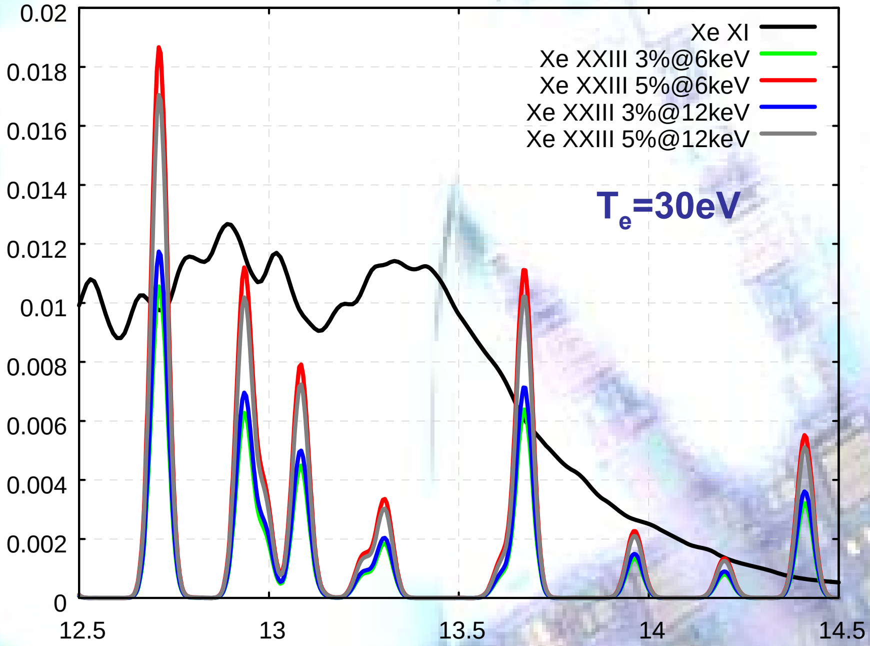
Optimization by gas mixture pressure

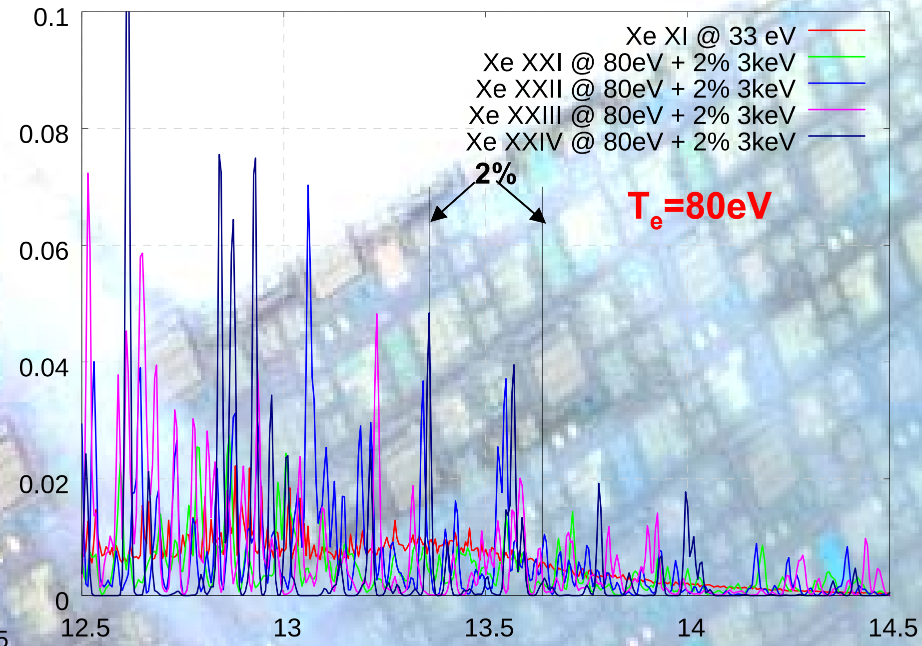
EUV source scan by stored electrical energy

Resistive regime



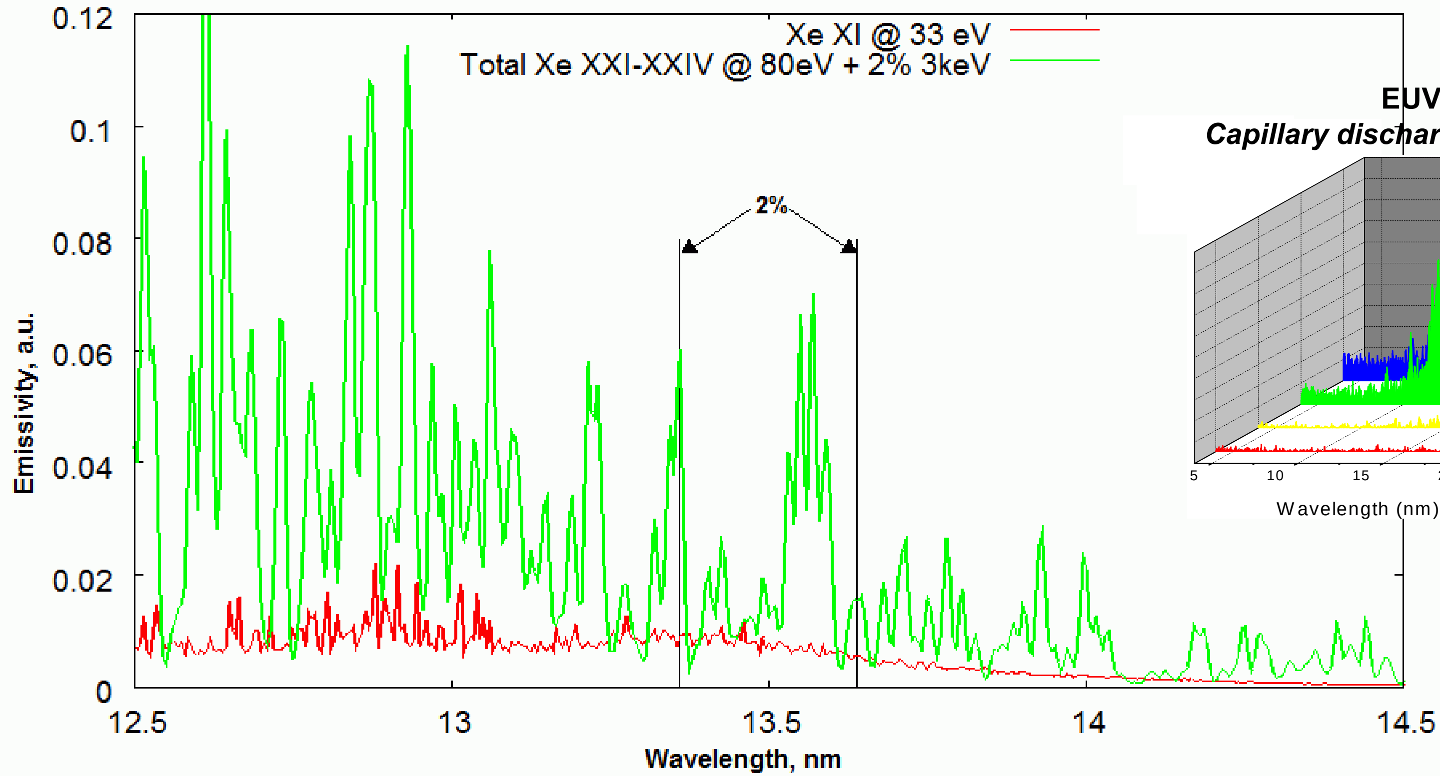
EUV Emission of Highly Charged Xe Ions
- from plasma with fast electrons



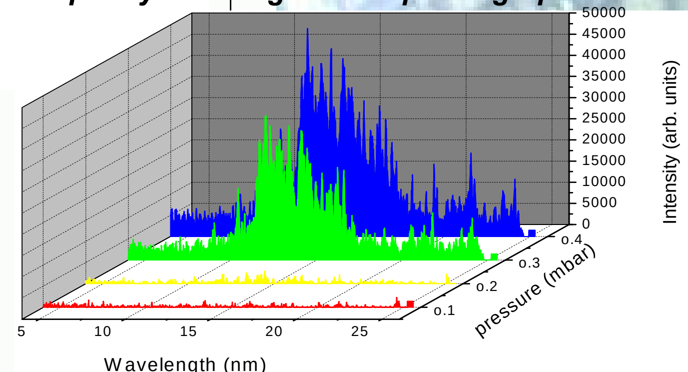


To produce the maximum EUV light power the double condition is required:
+ fast electrons have the energy of few keV to produce the highly charged ions
+ plasma has the temperature sufficient for the excitation of required transitions

EUV Emission of Highly Charged Xe Ions
- from e-beam triggered discharge plasma

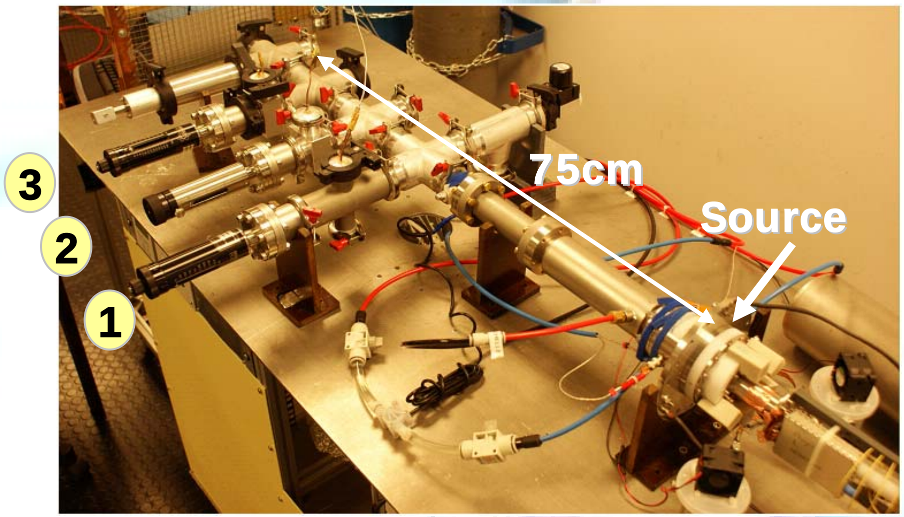


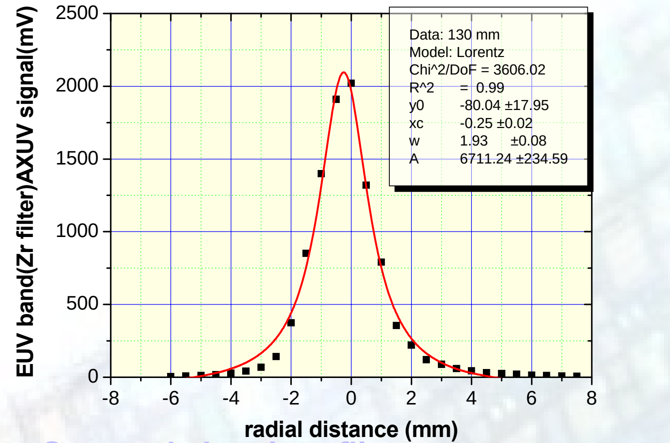
EUV Measurement
Capillary discharge. VUV spectrograph data



Bright EUV emission in 2% band at 13.5 nm can be achieved from highly charged xenon ions in plasma with small percentage of fast electrons

Focusing Effect Observation





Scanned signal profile

EUV band (Zr filter) radiation beam profile at 130mm from collimator exit

$$n^2 = 1 - \frac{\omega_e^2}{\omega^2} f_1(\omega)$$

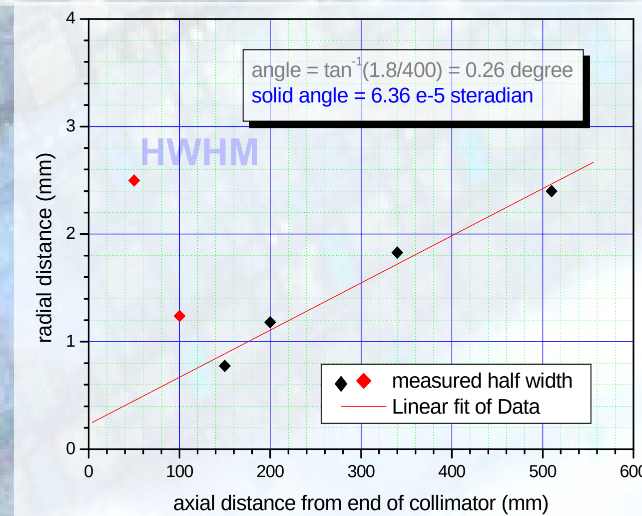
δn =/1-n/<<1;

δn ~ 0.01÷0.05 **(in solid matter) and**

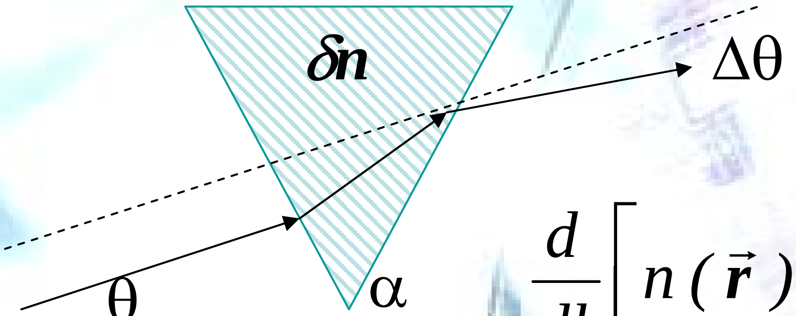
δn = 0.0000…. **(in plasma) for EUV range**

How it is possible in geometrical optics?

Know - How



Wave-guiding Refractive Structure



$$N = \frac{\theta}{\delta n \cdot \sin(\alpha)}$$ **refractions are required**

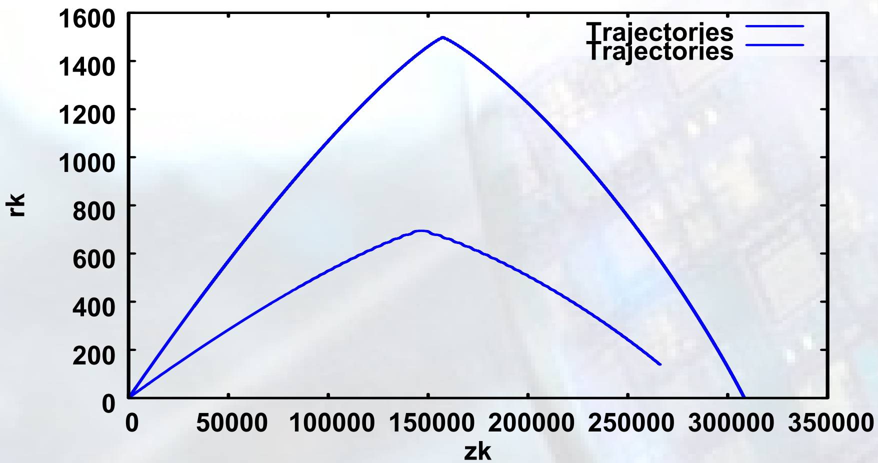
$$\frac{d}{dl}\left[n(\vec{r})\frac{d\vec{r}}{dl}\right] = \vec{\nabla} n(\vec{r})$$ **light trajectory equation**

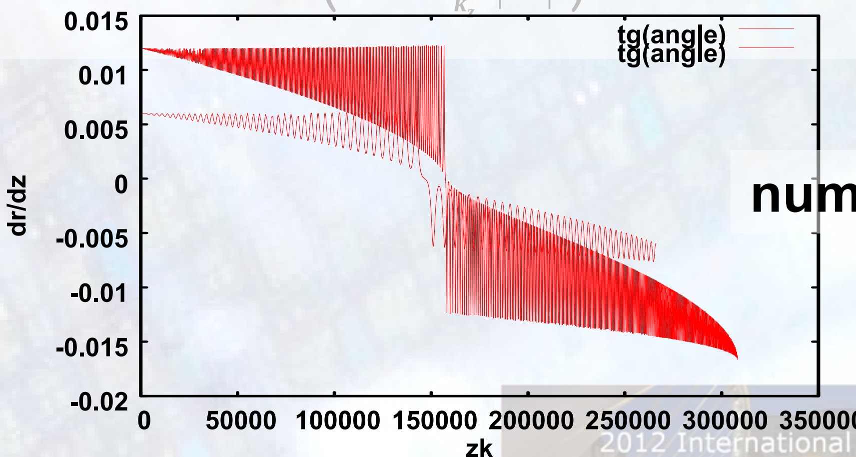
Refractive Structure: e-beam exited Kielwasser-waves, $k \le r_D^{-1}$

Focussing :

$$\bar{\theta}(z) - \theta_0 \approx -0.25 \int \frac{k_r |\delta n|^2}{\left(1 + 0.5 \frac{k_r^2}{k_z^2} |\delta n|^2\right)} dz$$ **analytical**

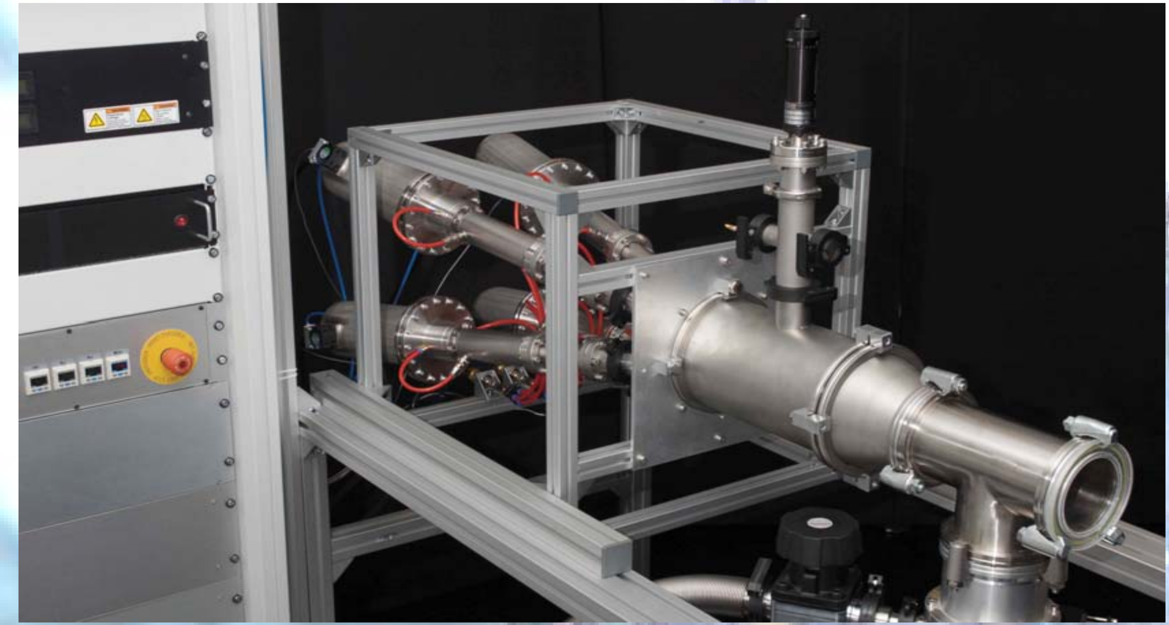
numerical

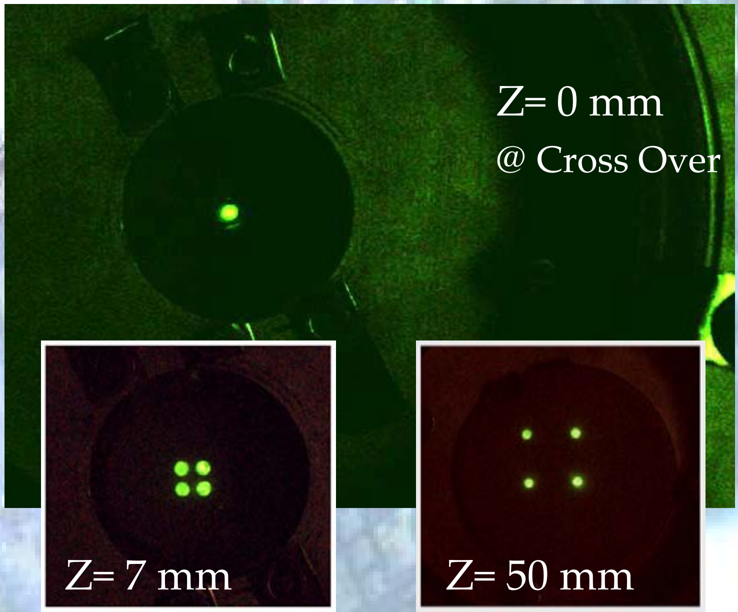




Multiplexer [4] :

- spatial multiplexing





4 sources operating individually with common power control

All 4 sources aligned to a point without use of any solid optical collector

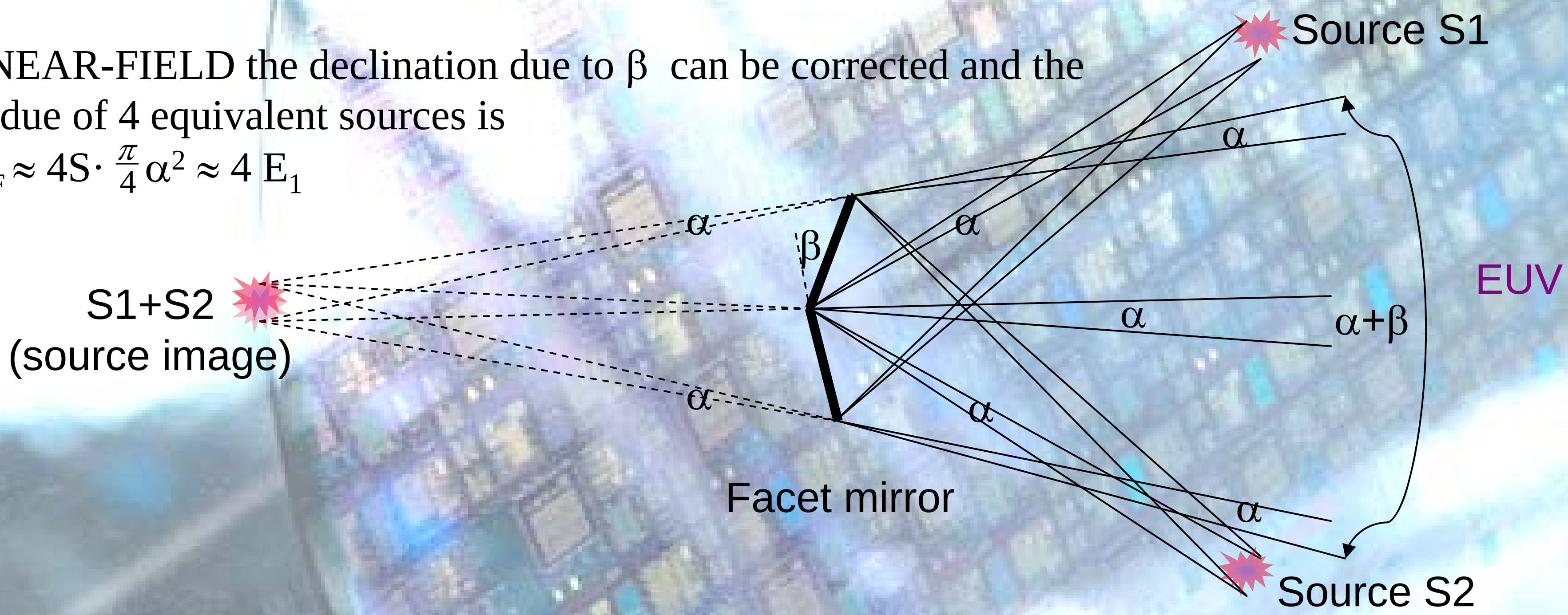
Multiplexer [4]: Optical Schematic

static combination of source beams to one

Etendue of a single source is $E_1 \approx S \cdot \alpha^2 \frac{\pi}{4}$

IN FAR-FIELD the etendue of 4 equivalent sources is
$E_{4FF} \approx 4S \cdot \frac{\pi}{4}(\alpha+\beta)^2 \approx 16\ E_1$

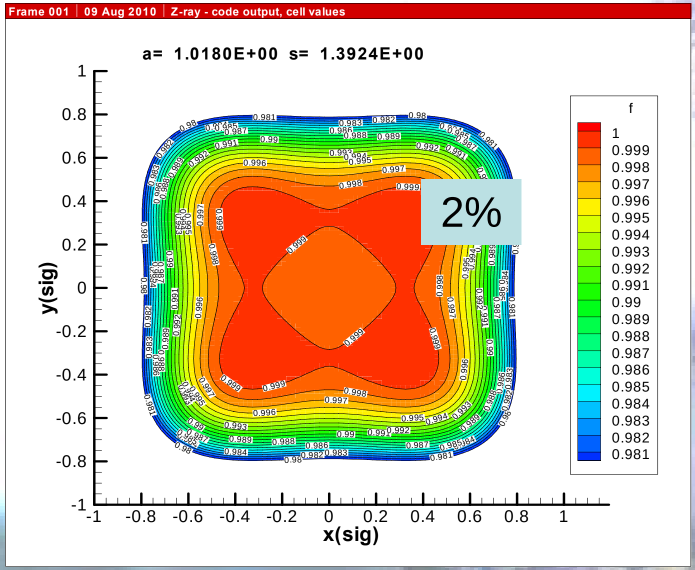
IN NEAR-FIELD the declination due to β can be corrected and the etendue of 4 equivalent sources is
$E_{4NF} \approx 4S \cdot \frac{\pi}{4}\alpha^2 \approx 4\ E_1$

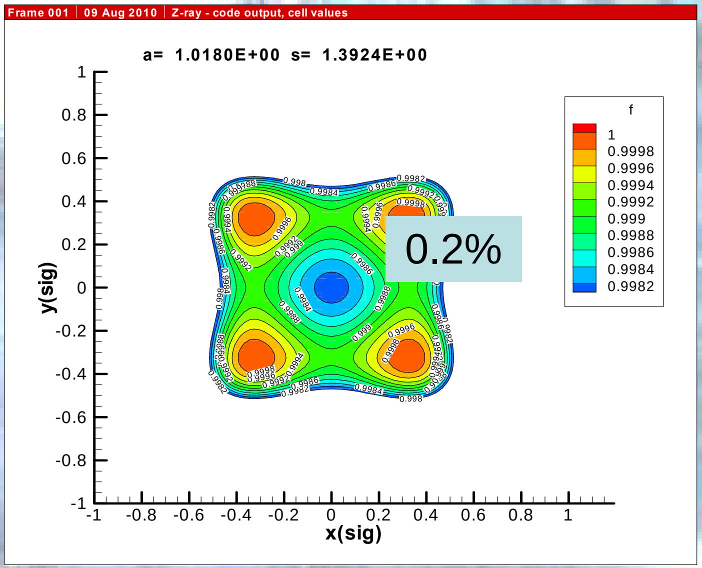


Multiplexer⁴:

- 4-beams flatness optimization

Overlapping of 4 suitably appertured Gaussian beam
at a given flatness of 2% or 0.2%



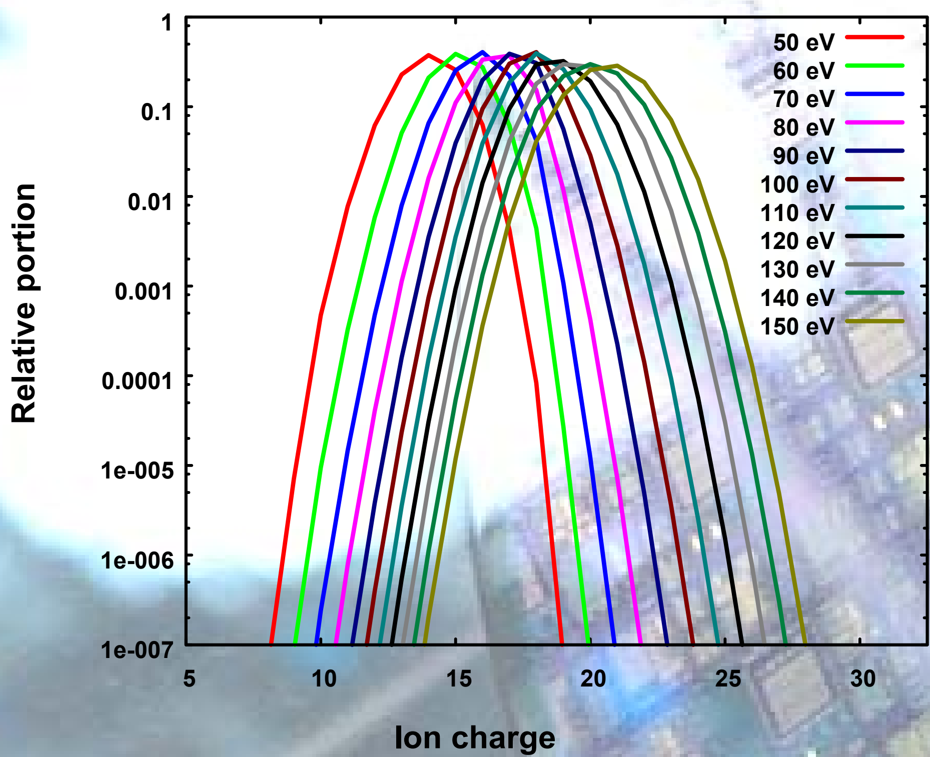


An efficiency with flatness of 0.2% is of ***22%.***

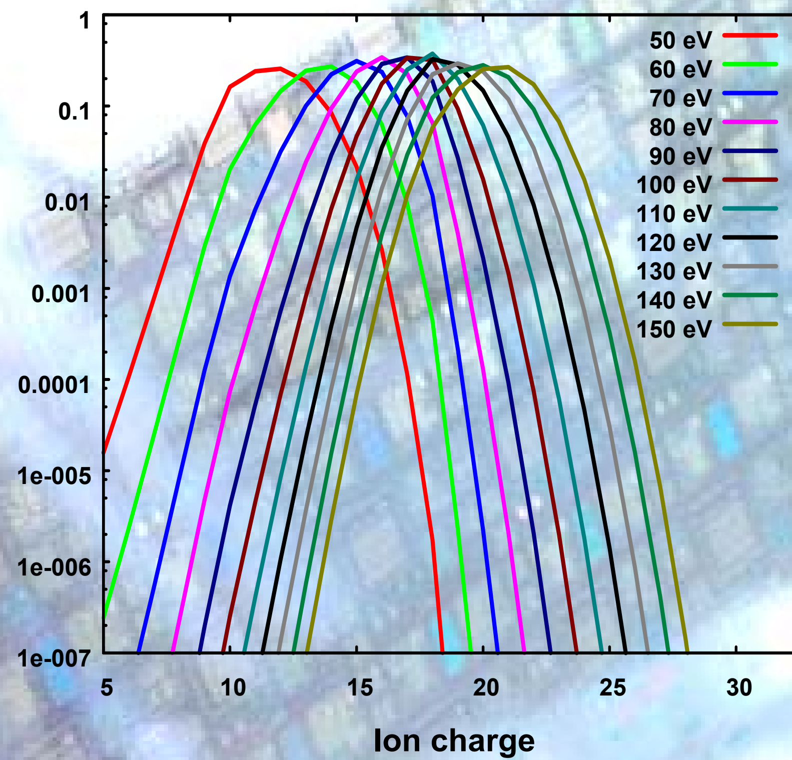
Gadolinium Plasma Emitting at 6.x nm

- Ion populations

$N_e = 10^{19}\ cm^{-3}$



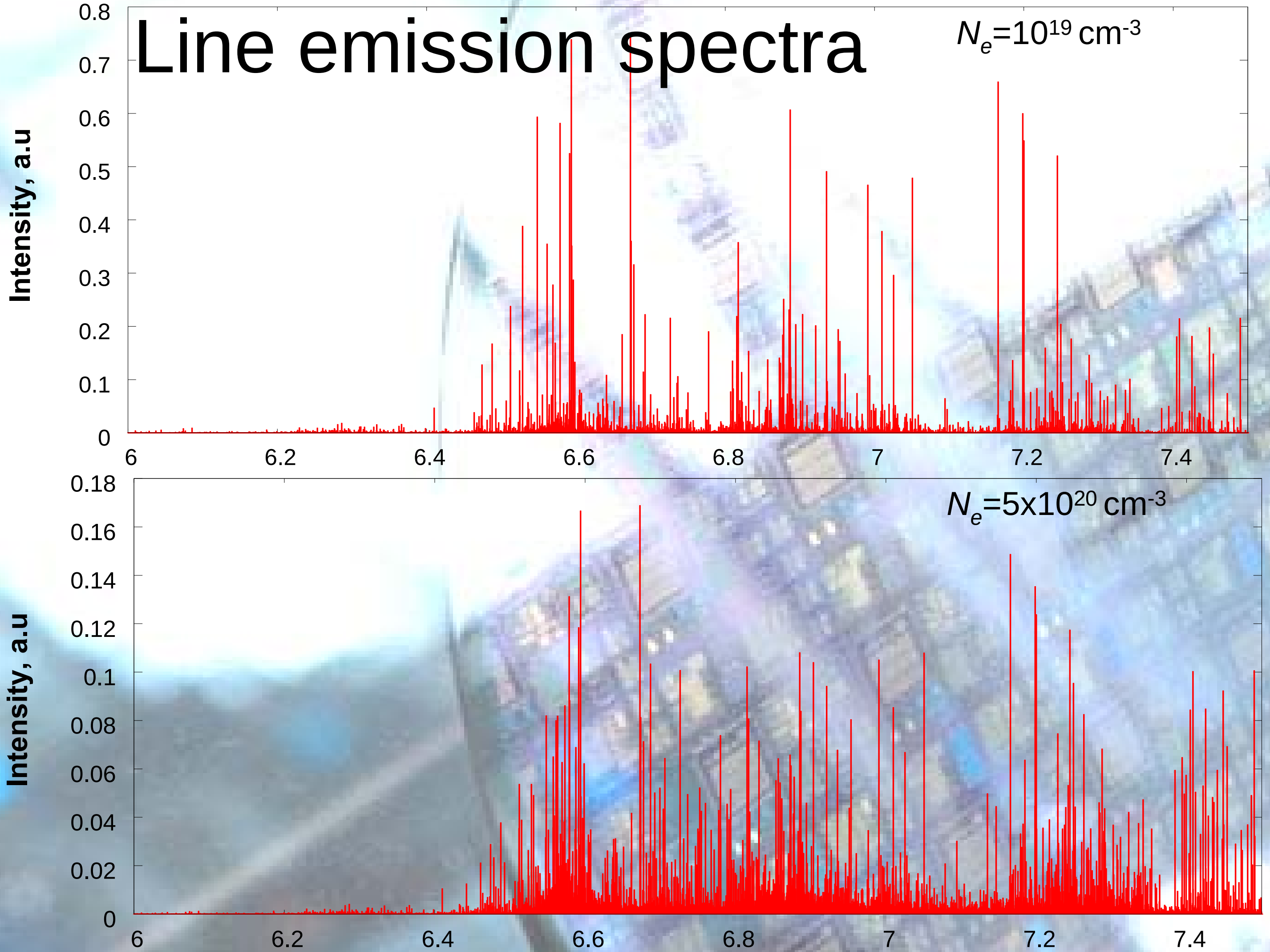
$N_e = 5x10^{20} cm^{-3}$



Ion distribution spreads and average charge drops as density increases →
→ for LPP very high temperature may be necessary

Gadolinium Emission

low temperature regime



T_e=60 eV

N_e=10^{19} cm^{-3}, 5x10^{20} cm^{-3}

Gd^{10+} - Gd^{18+} are taken into account

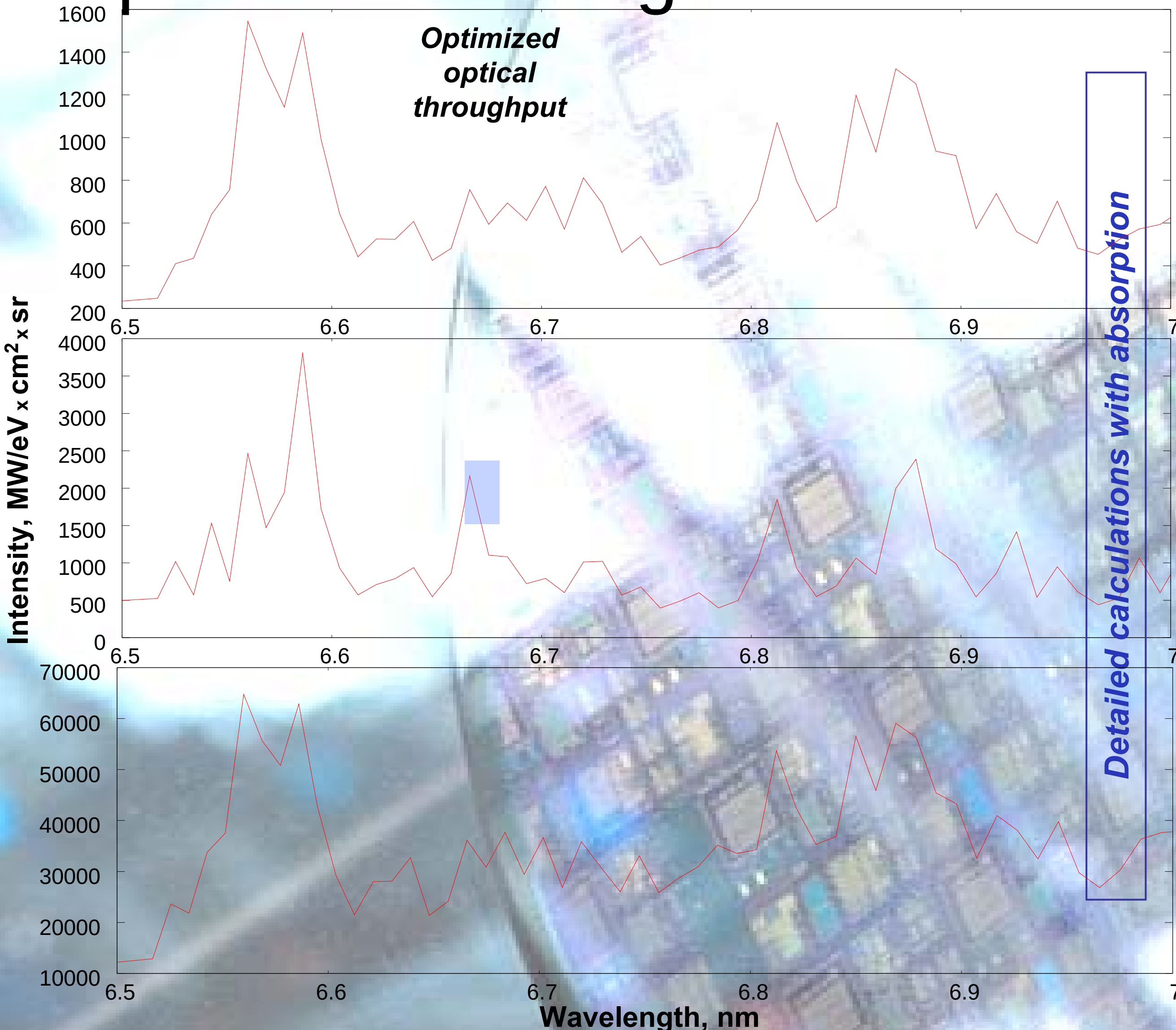
Almost 1 million transitions in total

More intensive emission is from 4f-4d transitions ($4d^9 4f^m$ – $4d^{10} 4f^{m-1}$)

Efficiency in Non-equilibrium Gd Plasma

low temperature regime

Spectral modeling



400 micron spherical Gd target

$N_e=10^{19}$ cm^{-3}, T_e=50 eV
SE @ 6.68 nm of 0.6% bandwidth 6.3%
SE @ 6.68 nm of 2% bandwidth 17.5%

$N_e=10^{19}$ cm^{-3}, T_e=60 eV
SE @ 6.68 nm of 0.6% bandwidth 5.3%
SE @ 6.68 nm of 2% bandwidth 18.5%

$N_e=5\times10^{20}$ cm^{-3}, T_e=60 eV
SE @ 6.68 nm of 0.6% bandwidth 5.9%
SE @ 6.68 nm of 2% bandwidth 16.8%

ZETA → Z* RMHD Code → Z* BME → Z+ multi-physics model

TABLES
nonLTE atomic & spectral data (Te,ρ,U)

RMHD (2D, 3D) with:
- spectral multigroup radiation transport in nonLTE;
- nonstationary, nonLTE ionization;
- sublimation – condensation;
- energy supply (electric power, laser)
- etc

EMHD or 3D PIC with:
ionization of weekly ionized plasma, discharge triggering

Discharge plasma simulation in real geometry Laser plasma

Data output:
$r,z,v,T_{e,i},\rho,E,B,Z,U_{\omega}$, etc;
visualization

Spectral postprocessing

Heat flux postprocessing

Z* Black-box Modeling Engine

Black-box Modelling Engine (Z*BME) is integrated into a specific computation environment to provide a turn-key simulation instrument, which does not require knowledge of numerical computation.

It has been adapted to simulate DPP and LPP radiation sources in a realistic geometry.

Z*BME has been installed:

in EUVA, Japan

in University College Dublin, Ireland

in Czech Technology University, Prague

A number of joint simulations of EUV radiation sources with Z* -code of Cymer, Bochum University, Xtreme Tech, FOM, EUVA, UCD, Bruker has been performed in frameworks of collaborations and FACADIX, MoreMoore, Medea+, FIRE projects

Next Generation Modelling Tools

fire
Fluid, Ions and Radiation Ensemble in Integrated Plasma Modelling

knowledge transfer in FP7 IAPP project

• FIRE - European FP7 Industry-Academia Partnerships and Pathways project

eppra
European Pulsed Power Research Applications

UCD DUBLIN

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• The FIRE project aims to substantially redevelop the Z^* code to Z^+ to include improved atomic physics models and full 3-D plasma simulation of

- ✓ plasma dynamics
- ✓ spectral radiation transport
- ✓ non-equilibrium atomic kinetics with fast electrons
- ✓ transport of fast ions/electrons
- ✓ condensation, nucleation and transport nanosize particles.

• Modelling is essential in parametric scans in radiation source optimization, in fast particles and debris generation to solve current EUVL source problems as well as extending their application.

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